ATMOSPHERIC TURBIDITY AT ATHENS, GREECE

GEORGE JAC. MACRIS

National Observatory, Athens, Greece [1]

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ABSTRACT

The turbidity of the cloudless sky at Athens, Greece, is investigated by means of pyrheliometric measurements made with No. 116 Kipp-Zonen pyrheliometer at the National Observatory, Athens. The measurements are based on observations of the direct sun radiation using two filters (red and yellow) and without a filter. The monochromatic turbidity is defined and used to compare the atmospheric transmission at Athens with the theoretical value for a Rayleigh (molecular)atmosphere. The results give an indication of the *unique* clarity of atmosphere in the Attica area.

1. INTRODUCTION

Local studies of the phenomena of solar radiation during its passage through the atmosphere are of great interest to all the physical sciences and particularly to meteorological physics. The study of the variation of intensity of solar radiation due to its attenuation by the atmosphere helps us to understand many physical characteristics of the structure and properties of the atmosphere. For example, from the turbidity we can draw some conclusions about the aerosol constitution of the atmosphere.

The purpose of this paper is to study daily variations of the turbidity of the atmosphere at Athens. The problem of the turbidity of the atmosphere is connected with the gradual extinction [2] of the solar radiation during its passage through the atmosphere [6], due to the absorption by gaseous constituents of the atmosphere, and the scattering by molecules and by larger particles that are known as aerosols, such as dust particles, sea salt particles, cloud droplets, etc. [11, 12]. This extinction or attenuation depends primarily on the length of the path of the solar radiation through the atmosphere. This depends on the zenith angle of the sun, as well as on the constitution of the atmosphere.

Regarding this problem some investigations have been carried out by Linke [8] and others. To determine the turbidity of the atmosphere, Linke evaluated the term $\frac{T'}{T}$, where T' is the observed or actual value of the optical thickness, and T the theoretical value of the Rayleigh or theoretical atmosphere (which is also often called the pure or molecular atmosphere). Although Linke based his study on the *mean value* of the optical thickness, he did notice some very important characteristics of the transmission of the solar radiation in the atmosphere.

The present study, in which optical thickness values for *each wavelength* are used, is based on radiation data from the solar radiation station established at the National Observatory at Athens in 1953 at the suggestion of Professor E. Mariolopoulos of the University of Athens [20]. Direct measurements of the solar energy are being made by using a No. 116 Kipp-Zonen pyrheliometer with yellow and red filters as well as with no filters. The transmitting regions of the filters used with the pyrheliometer are:

(1) yellow 28,000 Å, to 5,000 Å, (2) red 28,000 Å. to 6,000 Å. The pyrheliometer readings were taken at a specific time 11:20 (local civil time) only when the sky in the region of the sun was completely cloudless, which is usually expressed in S^4 in the Mörikofer Scale. (According to Mörikofer's Scale, S^0 means that the sun is completely obscured by clouds and S^4 means the sun is completely uncovered by clouds.)

2. DETERMINATION OF THE TURBIDITY

In this report, the values of the optical thickness were used for each wavelength, because it has been emphasized [15] that the effects of the transmission of solar energy will be more distinct if we use values of the turbidity factors for each wavelength by computation of the following ratios:

$$a=\frac{Q_B(\lambda)-Q_y(\lambda)}{Q'_B(\lambda)-Q'_y(\lambda)}=\frac{T_b}{T'_b}$$

$$b=\frac{Q_y(\lambda)-Q_r(\lambda)}{Q'_y(\lambda)-Q'_r(\lambda)}=\frac{T_y}{T'_y}$$

$$c=\frac{Q_y(\lambda)}{Q'_y(\lambda)}$$

$$p=\frac{Q_r(\lambda)}{Q'_r(\lambda)}$$

[1] Research performed during author's stay at University of California, Los Angeles, Calif.

[2] The annual depletion of the solar energy at Athens, Greece, was studied in reference [10].

where

$Q'_B(\lambda)$ and $Q_B(\lambda)$ denote the actual and theoretical amount, respectively, of solar energy in the spectral region $0.3 \leq \lambda \leq 2.8\mu$ (white light), falling on a normal surface at sea level in ly./min. (gram-calories per cm.^{2} per min.)

$Q'_y(\lambda)$ and $Q_y(\lambda)$ denote the actual and theoretical amount, respectively, of solar energy in the spectral region $.515 \leq \lambda \leq 2.8\mu$ (yellow filter of the instrument) falling on a normal surface at sea level in ly./min.

$Q'_r(\lambda)$ and $Q_r(\lambda)$ denote the actual and theoretical amount, respectively, of solar energy in the spectral region $.625 \leq \lambda \leq 2.8\mu$ (red filter of the instrument) falling on a normal surface at sea level in ly./min.

The ratio $\frac{T_b}{T'_b}$ will be defined as the turbidity for the spectral region $.3 \leq \lambda \leq .515\mu$. The ratio $\frac{T_y}{T'_y}$ is for the spectral region $.515 \leq \lambda \leq .625\mu$. Also the ratio $\frac{Q_y}{Q'_y}$ is called the turbidity for the spectral region of the yellow filter of the instrument $.515 \leq \lambda \leq 2.8\mu$ and the ratio $\frac{Q_r}{Q'_r}$ is called the turbidity for the particular spectral region of the red filter of the instrument $.625 \leq \lambda \leq 2.8\mu$. Since the values of $Q'(\lambda)$ were determined from the pyrheliometric measurements, in our problem the theoretical values of $Q(\lambda)$ only are to be computed.

These values can be obtained by evaluating the integral

$$Q(\lambda_1, \lambda_2) = \int_{\lambda_1}^{\lambda_2} I_o(\lambda)\, T(\lambda) d(\lambda) \tag{1}$$

where λ_1 and λ_2 represent the wavelength limits which apply, $I_o(\lambda)$ is the specific intensity of solar radiation, and $T(\lambda)$ is the fractional transmission of the filter, both at the wavelength λ. Expression (1) then represents the extraterrestrial theoretical values of the amount of the solar energy at the top of the atmosphere received through the filter of transmission $T(\lambda)$.

To apply the above computation to the surface of the earth it has to be formulated in the following way:

$$Q(\lambda_1, \lambda_2) = \int_{\lambda_1}^{\lambda_2} I_o(\lambda)\, T(\lambda) e^{-\tau \sec \theta} d_\lambda \tag{2}$$

where $e^{-\tau \sec \theta}$ is the transmission coefficient as given from the extension of the Bourger-Langley law for the pure molecular atmosphere [2, 16, 17, 18, 19]. These coefficients were obtained by interpolating values of monochromatic normal thickness for pure molecular atmosphere as given by Deirmendjian [3, 4]. The expression for the optical thickness τ is

$$\tau = \int_0^\infty b_\lambda dz \tag{3}$$

TABLE 1.—*Optical thickness (τ) of the molecular atmosphere as function of the wavelength (λ in microns)*

λ	τ	λ			
0. 305	1. 0295	0. 605	0. 0667	0. 905	0. 0131
0. 355	0. 7484	0. 655	0. 0468	0. 955	0. 0109
0. 405	0. 4465	0. 705	0. 0346	1. 025	8.79×10^{-3}
0. 455	0. 2122	0. 755	0. 0264	1. 525	1.55×10^{-3}
0. 505	0. 1388	0. 805	0. 0204	2. 025	4.96×10^{-4}
0. 555	0. 0972	0. 855	0. 0162	2. 425	2.41×10^{-4}

where b_λ is the monochromatic attenuation coefficient, a function of the density and the refractive index of the atmospheric layer. z is the normal distance measured vertically above the sea level; sec θ is the factor often called air mass, where θ is the zenith distance of the sun.

The values of $I_o(\lambda)$ were determined graphically from Nicolet's table [13, 14]. The transmission $T(\lambda)$ of the filters was determined from tables for standard European red and yellow filters [1]. For greater accuracy both graphs were expanded. The values were plotted on separate graphs as a function of λ for the yellow and red filters. By interpolation the transmission of the filters for different wavelengths was obtained with an accuracy of 0.001. In the integration (2) the trapezoidal rule was used with $\Delta\lambda = 100$ Å.

The values of the optical thickness were used from the theoretical computations by Deirmendjian and Sekera [4, 5]. These values were plotted versus wavelength on logarithmic paper. In table 1 these values of the optical thickness are given as a function of wavelength. From the plot, the optical thicknesses for all the wavelengths in the regions of the filters were determined accurately to 0.001. Then the transmission coefficient was computed for the values of zenith distance varying from maximum solar altitude at the latitude of the solar radiation station at Athens, Greece. That is, the extinction coefficient was computed for the following values of the zenith distance $\theta = 15°, 30°, 45°, 50°, 55°, 60°, 65°$, and $70°$.

3. DISCUSSION OF THE NUMERICAL RESULTS

Using these extinction coefficients we are able to perform the integration (2) by numerical methods, using the trapezoid rule with $\Delta\lambda = 100$ Å. The final answers are recorded in table 2. These values express the amount of solar energy (ly./min.) that is received by a surface, normal to the rays, of one square centimeter at sea level for a pure molec-

TABLE 2.—*The variation of the transmission of the solar energy (ly./min.) in a Rayleigh atmosphere as a function of wavelength and zenith distance*

Spectral region	λ (in microns)	Zenith distance							
		15°	30°	45°	50°	55°	60°	65°	70°
White	0. 300–2. 800	1. 802	1. 785	1. 751	1. 734	1. 714	1. 686	1. 651	1. 599
Yellow filter	0. 515–2. 800	1. 283	1. 278	1. 268	1. 263	1. 256	1. 247	1. 234	1. 215
Red filter	0. 625–2. 800	1. 049	1. 047	1. 043	1. 040	1. 037	1. 033	1. 027	1. 018

ular atmosphere and for the indicated zenith distances. From these numerical values the three curves I, II, III in figure 1 were plotted. Curve I represents the region of wavelengths from 0.300 to 2.800μ. Curve II represents the region of wavelengths from 0.515 to 2.800μ (yellow filter of the instrument). Curve III represents the region of wavelengths from 0.625 to 2.800μ (red filter of the instrument). Thus, from the curves we are able to determine the values of the solar energy in ly./min. received by a normal surface of one square centimeter at sea level, and for any values of the zenith distance contained between the extreme values 15° to 70°, and of course for all the corresponding altitudes of the sun that are included in these two values.

Finally, we computed the ratios a, b, c, d, using for Q' values obtained during the period 1953 to 1957 from daily observations at 11:20 local civil time and for Q the corresponding theoretical values (same λ and elevation). The plot of these values versus the months is given in figure 2 for the spectral region 0.300 to 0.515, in figure 3 for the spectral region 0.515 to 0.625, in figure 4 for the yellow filter, and in figure 5 for the red filter. Figures 2–5 represent the computed turbidity for observations during a particular month separately for each of the years 1953–1957, with the total number of observations in a particular month given in the bottom line. The results we obtained can be summarized as follows:

1.—In figures 2–5 (except figure 3 in which it is not so clear) a simple annual variation in the turbidity of the atmosphere in Athens is clearly visible. This variation shows a maximum in the summer season and a minimum in the winter or early spring (March). The increased turbidity in summer months is most likely caused by an increase in the number of aerosol particles, as well as by an increase in the size of the particles due to the greater relative humidity in the summer. This is caused by the south to southwest wind and the high frequency of sea breezes bringing more water vapor over Athens. These interpretations apply to average conditions. It can be seen in figure 2 that there are exceptions to this and very low turbidity can occur on some summer days as well as high turbidity during some winter days. This results in increased absorption and scattering of solar energy.

The accumulation of aerosols during the summer months is due to many factors. Some of the more important ones are (1) the number of days of precipitation is very small [9, 20] and therefore only a small scavenging effect can be expected; (2) the sea breeze brings (a) aerosols from the industrial district over to Athens and (b) dust particles raised up by whirl winds which are caused by an interaction of northeast and southwest breeze; (3) the increased turbulence during the summer months raises dust from the dried inland vegetation.

2.—From figures 2 and 3 we can say that the deviation of the radiation characteristics of a turbid atmosphere from

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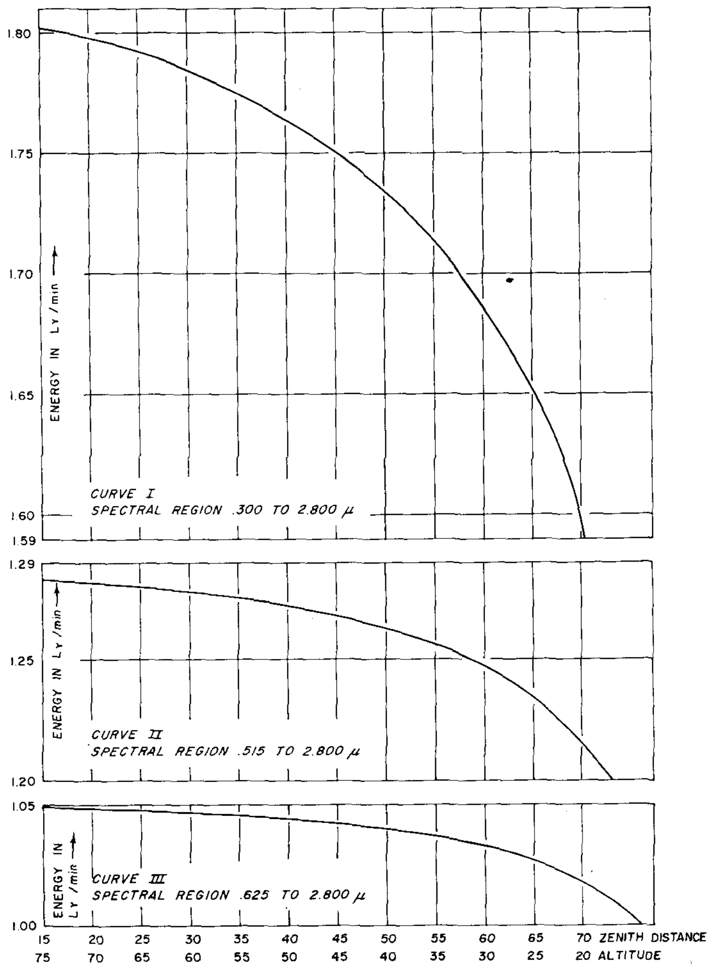

FIGURE 1.—Curves showing the variation of solar energy in a Rayleigh atmosphere with respect to zenith distance. Curve I is for white light; Curve II, using a yellow filter; and Curve III using a red filter.

that of a pure molecular atmosphere increases with the wavelength.

3.—The consequence of the above results is that the values of turbidity in the spectral region 0.300 to 0.515μ, figure 1, are smaller than the values of the turbidity as given in figures 3, 4, and 5. This indicates that the atmosphere in Athens under clear conditions does not differ from the pure molecular atmosphere. The reason for that probably is this: The atmosphere over the Attica area is very dry (the dryest of all Greece) as indicated from the observations of the relative humidity [9]. This probably explains the famous "Cyan" of the deep blue of the sky of Athens under clear conditions. Some earlier investigations of the blueness of the sky at Athens, Greece, were reported by L. Karapiperis and Ph. Karapiperis [7].

4.—Moreover, figures 2–5 confirm the results of turbidity determination from the measurements of sky light polarization performed under the direction of Prof. Z. Sekera at the University of California, Los Angeles [21].

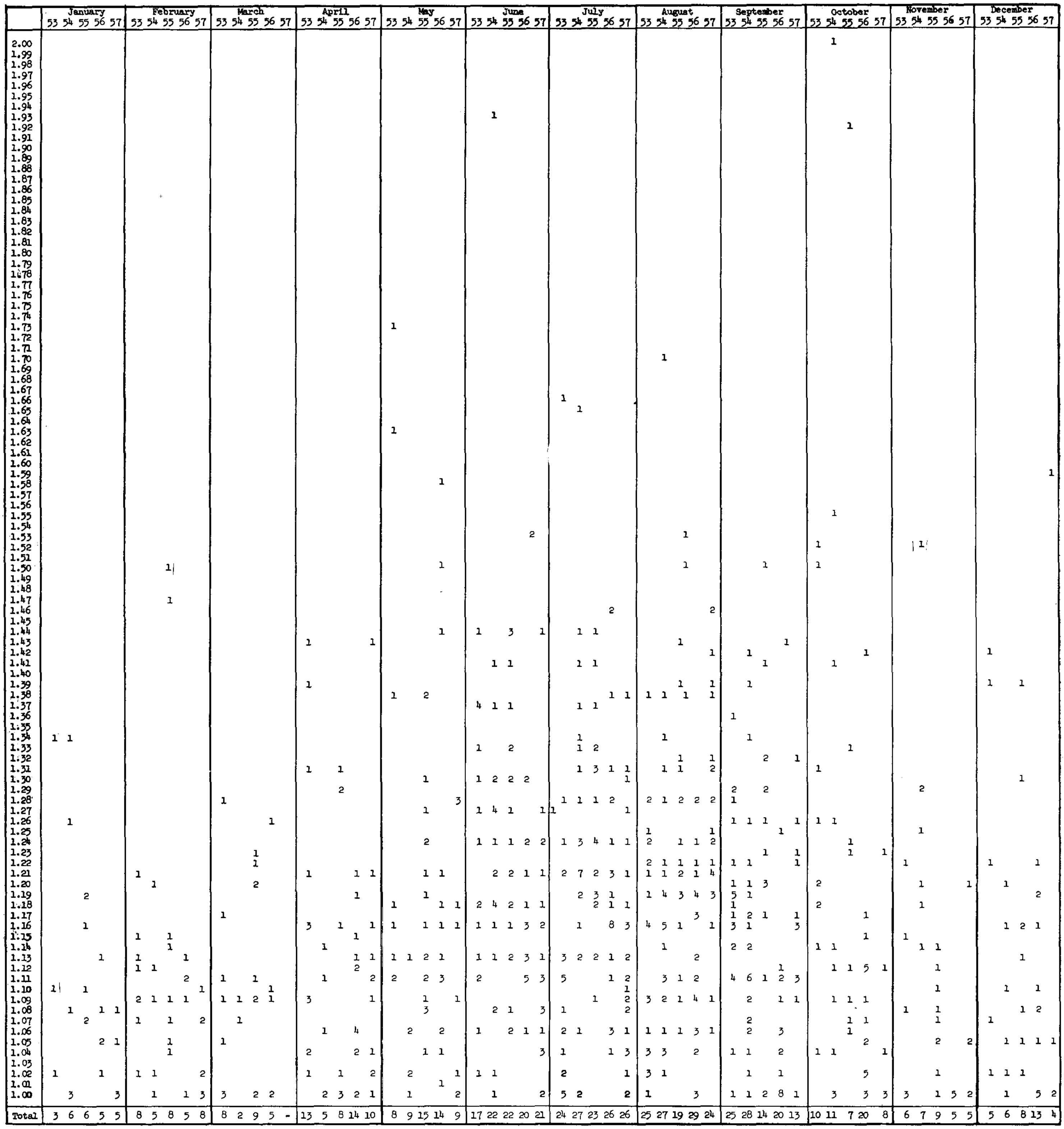

FIGURE 2.—Annual variation of the turbidity in the spectral region, 0.300 to 0.515 μ at Athens, Greece. The observation plotted at 2.00 is equal to 2.09.

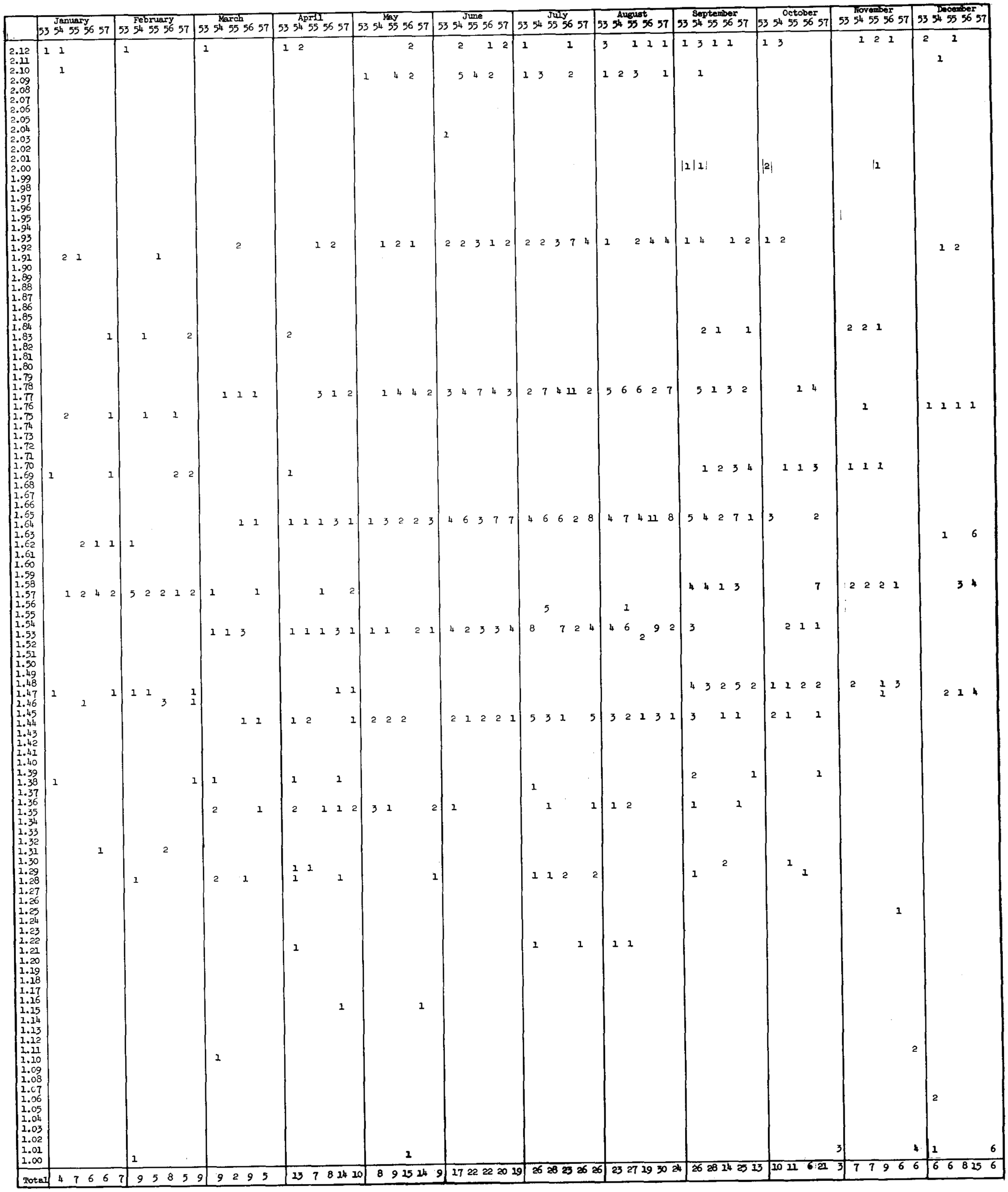

Figure 3.—Annual variation of the turbidity in the spectral region 0.515 to 0.625 μ at Athens, Greece. The observations plotted at 2.12 have a range from 2.20 to 5.75.

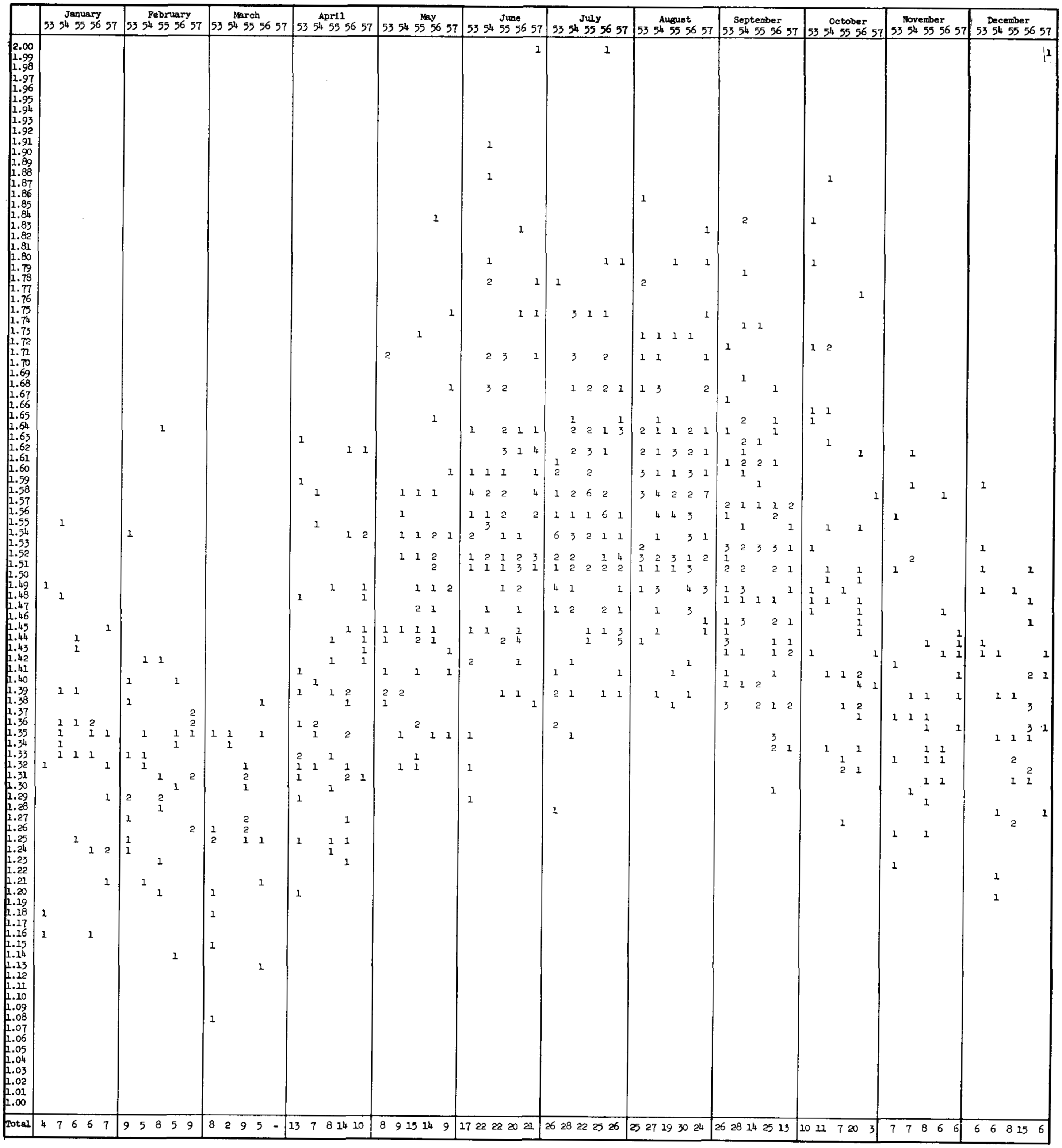

FIGURE 4.—Annual variation of the turbidity in the spectral region 0.515 to 2.800 μ at Athens, Greece. The observations plotted at 2.00 are equal to 2.13.

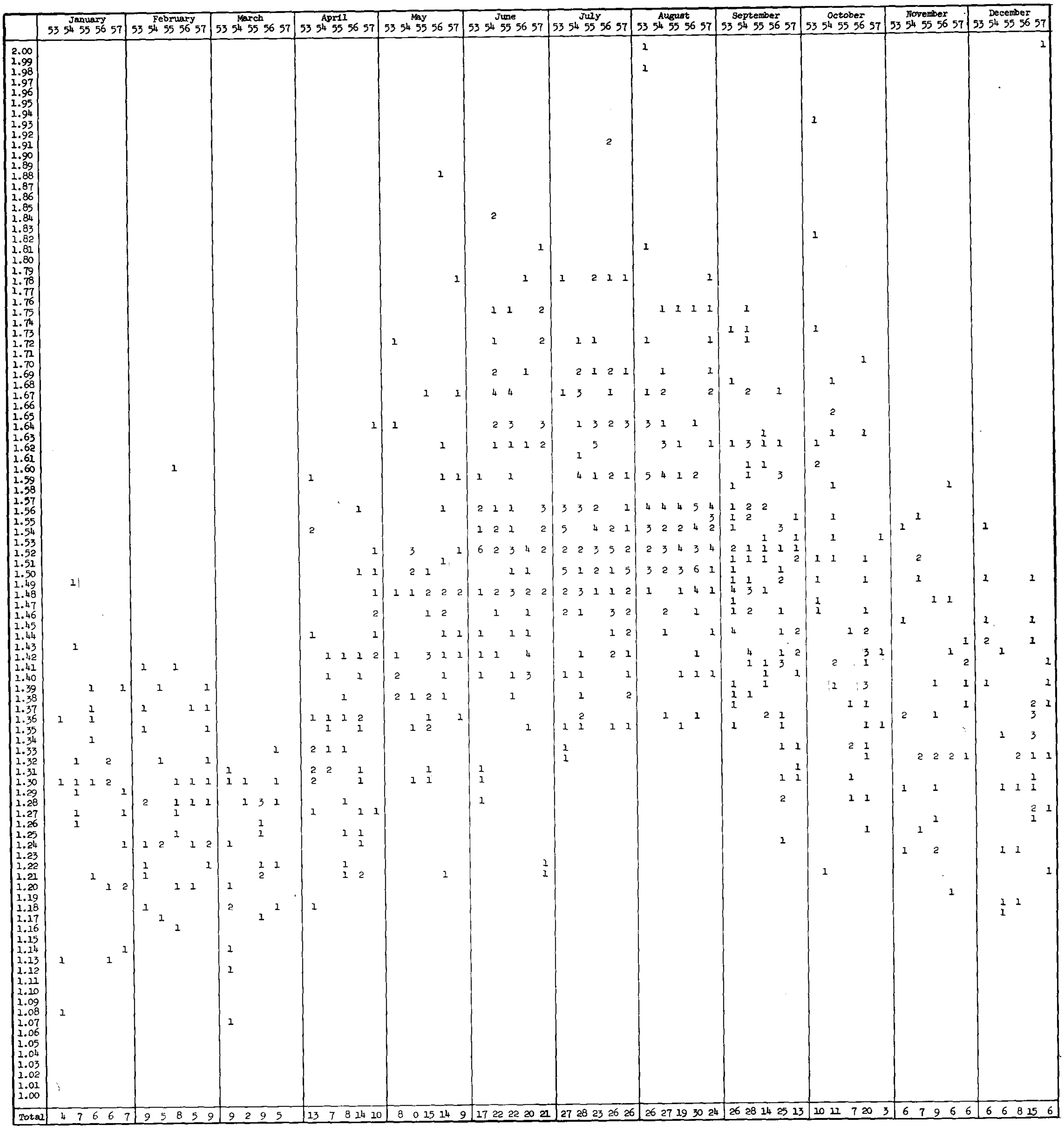

FIGURE 5.—Annual variation of the turbidity in the spectral region 0.625 to 2.800 μ at Athens, Greece. The observations plotted at 2.00 are equal to 2.02.

5.—Special interesting features are displayed by figure 3 as compared to figure 2. In figure 3 (spectral region 0.515 to 0.625μ) it is clearly shown that a certain distinctive degree of turbidity prevails during the winter and summer seasons. These turbidity values remained the same in the period 1953 to 1957. The values which appear to be more pronounced during the period March to October are about 1.44, 1.53, 1.64, 1.77, 1.92, 2.09; during the period September to December and January to February they are about 1.46–1.47, 1.57, 1.62, 1.69, 1.75. It seems as if this structure in the turbidity values is caused by special properties in the size distribution of the aerosols which appears to be constant for a particular air mass invading the Attica area.

This study proves quite clearly the advantages of the study of monochromatic turbidity [15, 16] and its potentialities in the study of relationships between the turbidity and the weather.

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REFERENCES

1. F. Baur et al., *Linkes Meteorologishes Taschenbuch*, vol. 2, New edition, Geestand Portig, Leipzig 1953, 724 pp. (See p. 520.)
2. F. Bernhardt, "Die Sekundär- diffuse Strahlung in einer Rayleigh-Atmosphäre," *ueitschrift für Meteorologie*. I: vol. 6, 1952, pp. 257–271. II: vol. 7, 1953, pp. 78–85.
3. D. Deirmendjian, "Attenuation of Light in the Earth's Atmosphere and Related Problems," *Scientific Report No. 1*, on Contract AF 19(122)-239, University of California, Dept. of Meteorology, 1952, 32 pp.
4. D. Deirmendjian, "The Optical Thickness of the Molecular Atmosphere," *Archiv für Meteorologie, Geophysik und Bioklimatologie*, Serie B, Band 6, Heft 4, 1955, pp. 452–461.
5. D. Deirmendjian and Z. Sekera, "Global Radiation Resulting from Multiple Scattering in a Rayleigh Atmosphere," *Tellus*, vol. 6, No. 4, Nov. 1954, pp. 382–398.
6. S. Fritz, "Solar Radiant Energy and Its Modification by the Earth and Its Atmosphere," *Compendium of Meteorology*, American Meteorological Society, Boston, Mass., 1951, pp. 13–33.
7. L. Karapiperis and Ph. Karapiperis, "Peri tou Kyanou Chrōmatos tou ouranour en Athēnais [On the Blueness of the Sky at Athens], *Praktica, Akademia Athēnōn*, vol. 27, 1952, pp. 211–215.
8. F. Linke, "Die Sonnenstrahlung und ihre Schwächung in der Atmosphäre," *Handbuch der Geophysik*, Band 8, Gebr. Borntraeger, Berlin, 1942, 1943.
9. E. G. Mariolopoulos, *The Climate of Greece*, A. A. Papaspyros, Athens, Greece, 1938.
10. G. Macris, "Solar Energy and Sunshine Hours at Athens, Greece", *Monthly Weather Review*, vol. 87, No. 1, Jan. 1959, pp. 29–32.
11. M. Neiburger, "The Reflectivity of the Sea Surface for Diffuse Radiation," *Transactions, American Geophysical Union*, vol. 29, 1948, pp. 647–652.
12. M. Neiburger, "Reflection, Absorption, and Transmission of Insolation by Stratus Cloud," *Journal of Meteorology*, vol. 6, No. 2, Apr. 1949, pp. 98–104.
13. M. Nicolet, "La mesure du rayonnement solarie," Institut Royal Meteorologique du Belgique, *Miscellanées*, Fasc. xxi, 1948, pp. 3–37.
14. M. Nicolet, "Sur la determination du flux energetique du rayonnement extraterrestre du Soleil," *Archiv für Meteorologie, Geophysik und Bioklimatologie*, Serie B, vol. III, Number 3, 1951, pp. 209–219.
15. Z. Sekera, "Polarization of Skylight," *Handbuch der Physik*, vol. 48, 1957, pp. 288–327.
16. Z. Sekera, "Polarization of Skylight," *Compendium of Meteorology*, American Meteorological Society, Boston, Mass., 1951, pp. 79–90.
17. J. W. Strutt (Lord Rayleigh), "On the Light from the Sky, its Polarization and Colour," *Philosophical Magazine*, vol. 41, 4th series, 1871, pp. 107–120, 274–279.
18. Lord Rayleigh, "On the Electromagnetic Theory of Light," *Philosophical Magazine*, vol. 42, 5th series, 1881, pp. 81–101.
19. Lord Rayleigh, "On the Transmission of Light through an Atmosphere Containing Small Particles in Suspension, and on the Origin of the Blue of the Sky," *Philosophical Magazine*, vol. 47, 5th Series, 1899, pp. 375–384.
20. National Observatory, *Climatological Bulletin*, Athens, Greece.
21. University of California at Los Angeles, Dept. of Meteorology, "Investigation of Polarization of Skylight," *Final Report* on Contract AF 19(122)-239, June 1955, 68 pp.